1.0 Technology Validated

The DS1 spacecraft uses a single-engine, xenon ion propulsion system, provided by the NASA Solar electric propulsion Technology Applications Readiness (NSTAR) project, for primary on-board propulsion.

Technology validation requirements for the NSTAR Project were developed early in the Project life cycle. A QFD exercise conducted in 1993 resulted in a documented set of user, customer, stakeholder, and sponsor needs that the NSTAR Project needed to satisfy in order to be declared successful. All items from that complete list are shown in this report along with the benchmark data that was demonstrated in flight. One of the prime objectives of the project was to satisfy future users that this technology was flight-proven, therefore retiring the perceived risk issues was a significant part of the validation effort. The details of these efforts are described in the full report. Some of these important issues were retired through an extensive ground test program while the others were retired through the flight test on DS1.

2.0 Risks Associated with this Technology

The following key risks were addressed by the NSTAR project as part of ground testing and during the flight of the ion propulsion system on DS1:

1. Adequate engine life – prior to the NSTAR project no ion engine intended for primary propulsion had ever been successfully operated for its full design life.
2. Guidance, Navigation and Control of an SEP spacecraft – the low-thrust nature of SEP, together with large solar arrays makes GN&C sufficiently different from conventional deep-space spacecraft that this is a significant risk area.
3. Mission operation costs – SEP systems require the propulsion system to operate continuously for long periods of time leading some observers to project that a standing army of propulsion and power engineers would be required to operate the spacecraft resulting in high mission operations costs.
4. Spacecraft contamination by the SEP system – slow erosion of the engine results in a non-propellant efflux from the thruster that could contaminate sensitive spacecraft surfaces.
5. SEP impacts on science instruments – the charge-exchange plasma generated by the operation of the SEP system is easily detected by on-board plasma instruments.
6. SEP impacts on communication – the charge-exchange plasma generated by the operation of the SEP system, as well as the primary beam plasma, could affect the transmission or reception of electromagnetic waves.
7. Electromagnetic compatibility (EMC) of the SEP system with the spacecraft – the high-power nature of SEP and the use of strong permanent magnets in the ion engines could make it difficult for the SEP system to be electromagnetically compatible with the spacecraft.

How these risks were successfully retired is discussed in the full report.

3.0 Validation Objectives and Approach

The NSTAR project was designed to overcome the barriers preventing the use of SEP on deep-space missions and enable ion propulsion to enter the mainstream of deep-space propulsion options. To accomplish this, the project had to achieve two major objectives:

1. Demonstrate that the NASA 30-cm diameter ion engine had sufficient life and total impulse capability to perform missions of near-term interest.
2. Demonstrate through a flight test that the ion propulsion system hardware and software could be flight qualified and successfully operated in space, and demonstrate control and navigation of an SEP-based spacecraft.

To demonstrate sufficient engine life the ground test program was designed to first demonstrate 100% of the engine design life, and subsequently to demonstrate 150% of the engine life. The flight of the NSTAR system on DS1 addressed the integration, compatibility, and operations issues associated with the use of SEP on a deep space mission.

4.0 Test Program

The NSTAR test program employed an extensive ground test activity together with the flight test on DS1 to validate the ion propulsion technology.

The NSTAR ground test program was planned around the use of engineering model thrusters (EMTs) build by NASA GRC and eventually flight model thrusters fabricated by HED. A total of four EMTs and two sets of flight hardware consisting of thrusters, power processor units (PPUs) and digital interface & control units (DCIUs) were fabricated and tested. In addition, the NSTAR project designed and fabricated an engineering model xenon feed system. The flight xenon control assembly (XCA) was fabricated by Moog. The four EMTs enabled a series of over 40 engineering tests which addressed wear mechanisms, thermal behavior, mechanical fidelity, low power performance, and, finally, lifetime in order to instill confidence in the thruster design. An 8000-hour life test demonstrated, for the first time in history, that an ion engine for primary propulsion could be successfully operated for its full design life.

The two sets of flight units were subjected to acceptance and qualification testing, after which selected flight units were delivered to the spacecraft for the DS1 test program and, ultimately, for flight. The spare flight set is, as of this writing, being used in an extended life test to demonstrate 150% of the engine design life.

5.0 Test Results

Ground Tests: Early tests of the GRC-built engineering model thrusters validated an initial set of design features and enabled measurement of engine component wear under a variety of thruster operating conditions. A 2000-hour test of EMT1 led to design improvements which were successfully verified in a subsequent 1000-hour test of this thruster. These tests resulted in a final design which was incorporated into the second engineering model thruster, EMT2. This thruster was used in the Life Demonstration Test (LDT), which was designed to operate the thruster for 8000 hours at full power.

The LDT was the most successful endurance test of a high-power ion engine ever performed. A total of 8,192 hours of operation were achieved at an input power of 2.3 kW with a specific impulse of 3200 s before it was voluntarily terminated. A total of 88 kg of xenon propellant was processed, demonstrating a total impulse of 2.73×10^6 N-s. Risks associated with neutralizer lifetime, thrust performance degradation, engine efficiency degradation, material deposition, thrust vector drift, electrode wear, long-term thermal characteristics, and initial start-up conditions were successfully retired by this test.

The last major test in the NSTAR project plan is the Extended Life Test (ELT) which is designed to demonstrate 150% of the engine design life using the DS1 flight spare engine (FT2). The engine design life is most easily expressed in terms of the total amount of xenon propellant that the thruster can process. For the NSTAR project, the engine design life is 82 kg of xenon, which corresponds to about 8,000 hours of operation at full power. To demonstrate 150% of the engine life, therefore, requires a test in which approximately 125 kg of xenon is processed by the engine. A secondary objective of this test is to demonstrate extended operation at throttled conditions since the previous project level life tests had all be performed at the full power point. It is believed that the full power point is the most stressing to the engine, however, the ELT is designed to obtain the data necessary to support this assertion.

As of this Symposium (February 2000), the ELT has operated FT2 for more than 8,000 hours covering three different throttle levels and has processed more than 75 kg of xenon. The test is scheduled to demonstrate the 125-kg throughput by the end of the year. The Deep Space Exploration Technology program is considering extending this test to determine the actual thruster end-of-life. This would significantly benefit the potential future users listed in Section 6.0 below.

Flight Test: Aside from an initial hick-up, the operation of the NSTAR ion propulsion system (IPS) on DS1 has been flawless.

The initial hick-up occurred 4.5 minutes after the engine was first started in space when continuous high-voltage recycling caused the thruster to shutdown. Subsequent troubleshooting efforts identified that the fault was most likely due to a piece of conductive debris lodged between the grids. To dislodge this debris the spacecraft was turned several times to move the ion engine in and out of the sun. This results in thermally cycling of the engine's ion accelerator system causing the electrodes to move relative to one another. Subsequently, another start attempt was made at thirty one days after launch and the engine started normally and has operated perfectly since this time.

As expected, operation of the ion engine, PPU and xenon feed system in space produced performance that closely matched that measured on the ground. In addition, the flight on DS1 enabled the following resolution of the key risk areas listed earlier:

1. Guidance, Navigation and Control – the operation of the SEP system on DS1 demonstrated that GN&C is not more difficult with and an SEP spacecraft, just different.
2. Mission Operation Costs – the electrical nature of SEP lends itself well to autonomous operation resulting in essentially no significant increase in mission operations cost for SEP vehicles.
3. Spacecraft Contamination – data from DS1 indicates that this efflux travels largely in line-of-sight from the engine and does not pose a significant health risk to a properly designed spacecraft.
7. SEP Impact on Science Instruments – DS1 showed that the low-energy charge-exchange plasma generated by the operation of the ion engine does not interfere with measurements of the much more energetic solar wind plasma
8. SEP impacts on communication – no impact of the SEP system operation on communications with DS1 could be detected.
9. Electromagnetic compatibility (EMC) of the SEP system with the spacecraft – DS1 showed that

while this issue requires careful engineering, it is an easily tractable problem.

6.0 Applicability & Potential Future Benefits

Many missions have been identified by JPL's advanced mission planning activity as being either enabled or strongly enhanced by the use of solar electric propulsion based on NSTAR or derivatives of the NSTAR ion propulsion technology including: Comet Nucleus Sample Return, Mercury Orbiter, Neptune Orbiter, Titan Explorer, Saturn Ring Observer, Europa Lander, and Venus Sample Return.

To illustrate the benefits enabled by the use of an NSTAR-derivative SEP system for a mission to a comet, the performce of a SEP-based spacecraft to the comet 46P/Wirtanen is compared to ESA's chemical-propulsion-based Rosetta mission to the same target. The Rosetta spacecraft has an initial wet mass of 2,900 kg and is launched on an Ariane 5. This spacecraft takes over 9 years to reach the comet, arrives with a net spacecraft mass of 1300 kg, and does not return a sample from the comet. An SEP-based spacecraft, on the other hand, with an initial wet mass of 1830 kg, could be launched on a Delta IV medium launch vehicle. The SEP system would take only 2.6 years to deliver a 1300-kg spacecraft to the comet. The same SEP system could then return the spacecraft and a comet sample to Earth in an additional 4.5. Thus, the SEP-based spacecraft could travel to the comet and return to Earth in less time than it takes for a chemical-propulsion-based spacecraft to fly to the comet!

7.0 Conclusions

The success of the NSTAR SEP system on the DS1 spacecraft, as well as the success of the NSTAR engine life test program has resulted in SEP now becoming a legitimet propulsion option for deep space missions. The project's successful validation effort now enables exciting new missions to benefit from the substantial performance capabilities of ion propulsion.